The PS longitudinal broadband impedance: comparison between measurements, theory and simulations

M. Migliorati, H. Damerau, S. Gilardoni, S. Hancock,
S. Persichelli, L. Palumbo

Dipartimento di Scienze
di Base e Applicate
per l'Ingegneria

Sapienza
Università di Roma

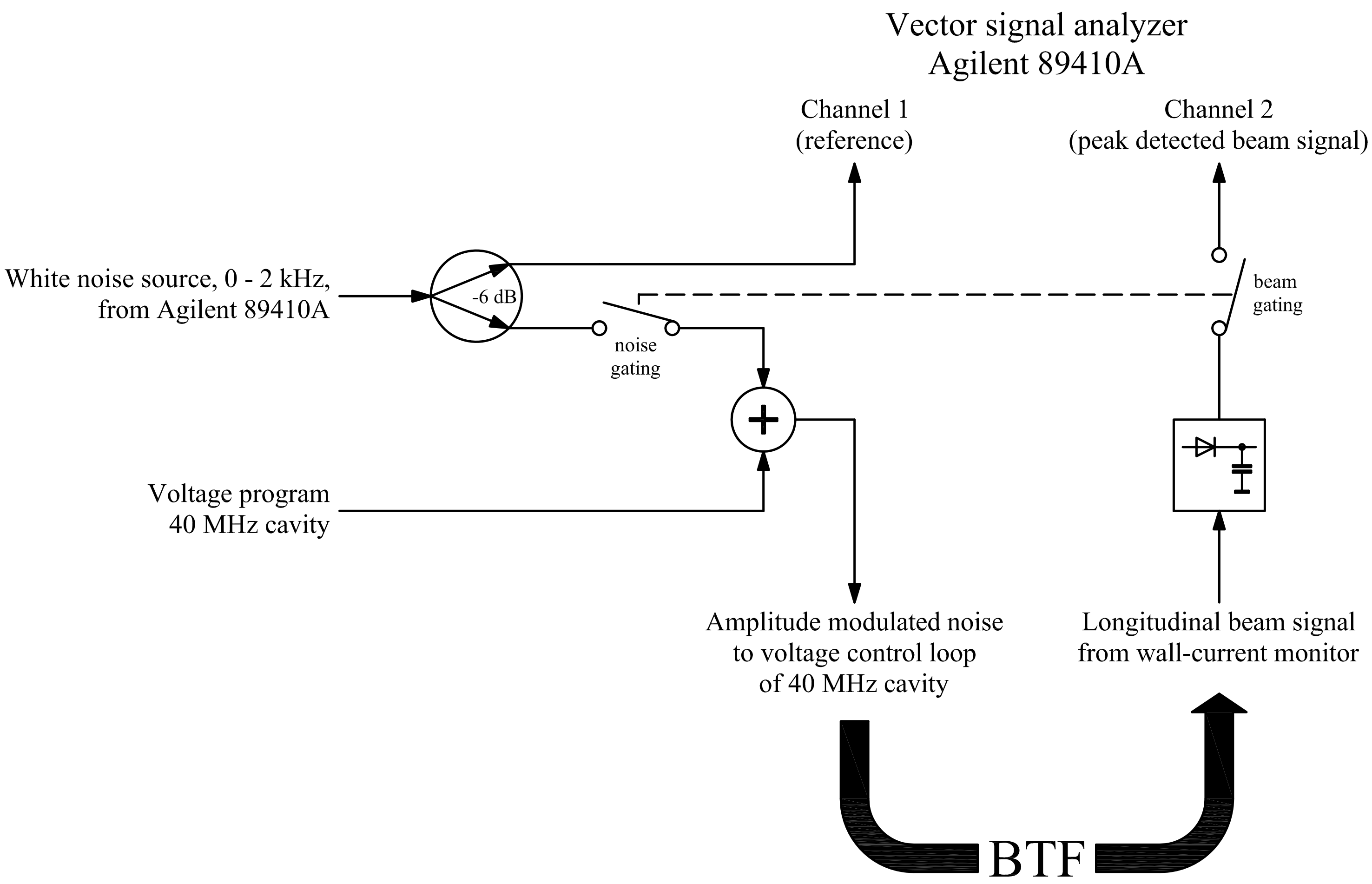
INFN
Istituto Nazionale
di Fisica Nucleare
Laboratori Nazionali di Frascati

Outline

- Measurements of the quadrupole incoherent synchrotron frequency shift vs single bunch intensity
- Results of data analysis and longitudinal broadband impedance value
- Comparisons with simulations
- Impedance budget
- Conclusions

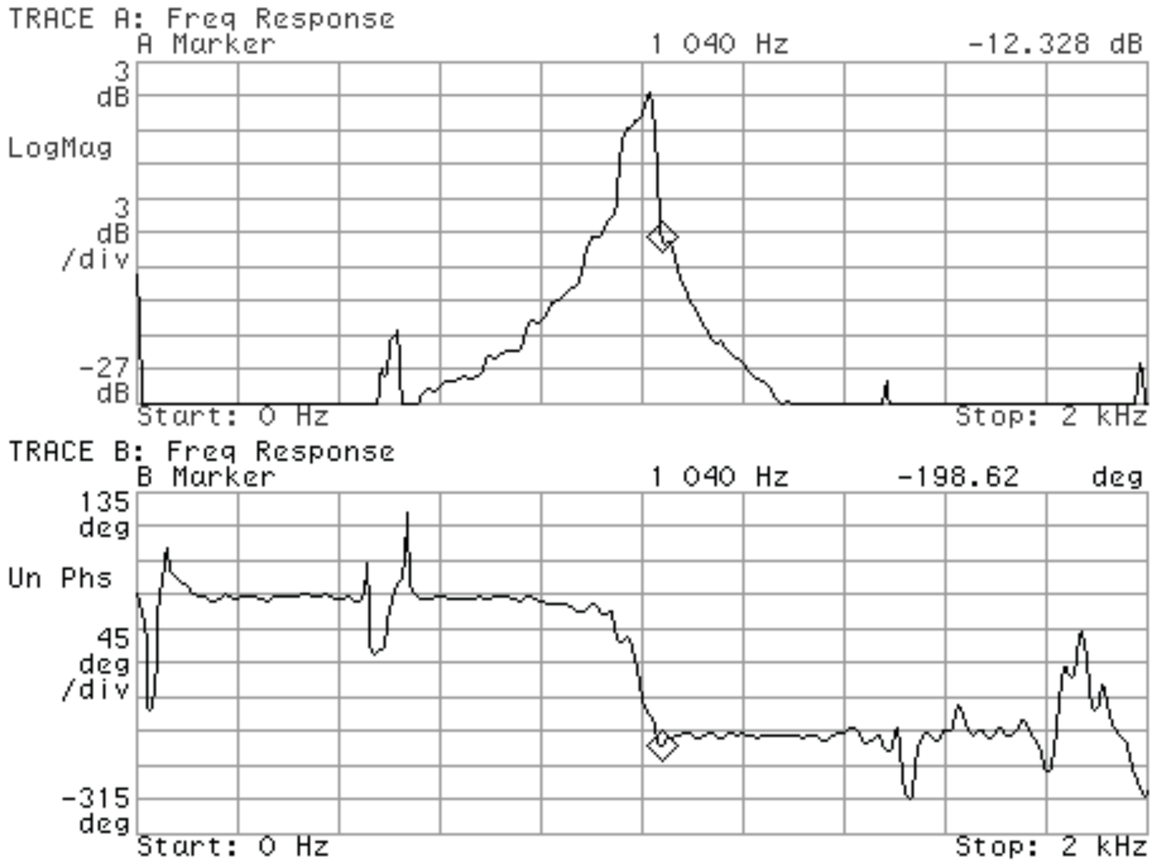
Measurements

- Single bunch measurements @ 26 GeV: set-up



Measurements

- Example of the beam signal on Agilent 89410A from wall-current monitor



Measurements

- Two MD sessions were dedicated to the measurements: on May 10th and on June 13th
- About one month of interval to verify the reproducibility of the measurements
- 40 MHz cavity with V_{RF} = 40 kV and 80 kV in the first MD and 47.5 kV and 95 kV in the second MD (changing also the 40 MHz cavity)
- ppb = (0.9 - 4.6) x 10^{11}
- Total bunch length = (9 - 14) ns
- Each measurement was taken by averaging over 16 acceleration cycles

Measurements

First set of measurements (10 May 2012)

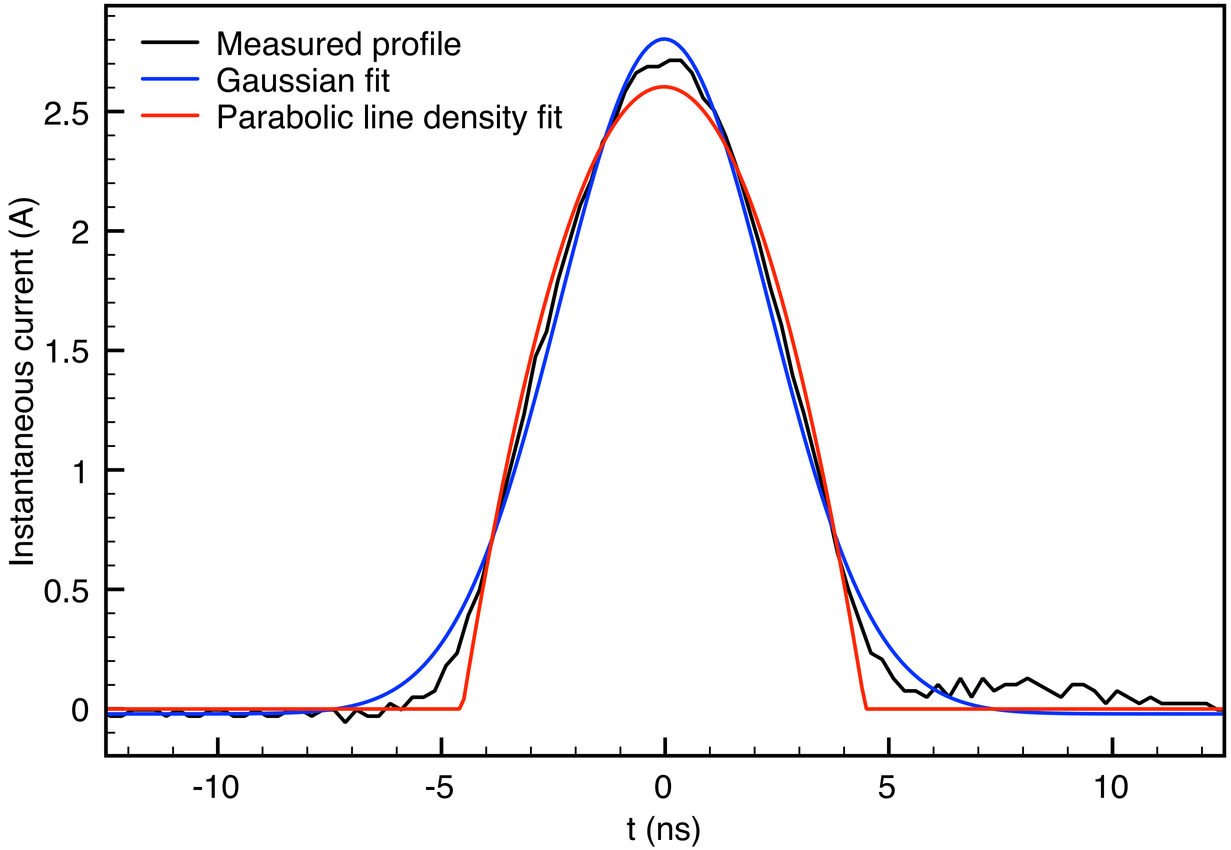
N_p (10^{11})	V_{RF} (kV) ± 5%	f_{2s} ± 12 (Hz)	σ_G (ns)	τ_b (ns)
1.40 ± 0.03	80	960	2.35 ± 0.01	9.07 ± 0.04
1.41 ± 0.02	40	675	2.83 ± 0.02	10.90 ± 0.08
4.42 ± 0.07	40	620	3.65 ± 0.03	13.83 ± 0.12
4.44 ± 0.08	80	895	2.95 ± 0.02	11.19 ± 0.06
3.19 ± 0.03	80	915	2.54 ± 0.01	9.73 ± 0.04
3.20 ± 0.03	40	640	3.12 ± 0.01	11.92 ± 0.03
2.29 ± 0.04	40	640	2.83 ± 0.02	10.90 ± 0.10
2.37 ± 0.03	80	930	2.39 ± 0.03	9.25 ± 0.12
2.30 ± 0.05	80	930	2.33 ± 0.03	9.01 ± 0.09
1.40 ± 0.01	80	955	2.94 ± 0.02	11.19 ± 0.09
1.43 ± 0.03	40	690	3.55 ± 0.02	13.50 ± 0.07

Second set of measurements (13 June 2012)

N_p (10^{11})	V_{RF} (kV) ± 5%	f_{2s} ± 12 (Hz)	σ_G (ns)	τ_b (ns)
4.34 ± 0.09	47.5	690	3.53 ± 0.03	13.44 ± 0.10
4.52 ± 0.13	95	980	2.92 ± 0.02	11.08 ± 0.08
4.57 ± 0.06	47.5	710	3.56 ± 0.005	13.52 ± 0.02
4.40 ± 0.09	95	970	2.90 ± 0.007	11.01 ± 0.02
2.70 ± 0.08	47.5	720	3.30 ± 0.01	12.76 ± 0.04
2.67 ± 0.08	95	1025	2.71 ± 0.009	10.48 ± 0.03
2.69 ± 0.04	47.5	700	2.95 ± 0.01	11.35 ± 0.05
2.62 ± 0.08	95	1020	2.42 ± 0.02	9.35 ± 0.06
1.70 ± 0.03	47.5	760	3.45 ± 0.007	13.26 ± 0.03
1.79 ± 0.04	95	1045	2.86 ± 0.009	11.06 ± 0.03
1.76 ± 0.03	47.5	735	3.01 ± 0.02	11.59 ± 0.05
1.79 ± 0.03	95	1025	2.49 ± 0.01	9.59 ± 0.05
0.88 ± 0.03	47.5	765	3.27 ± 0.01	12.46 ± 0.04
0.91 ± 0.02	95	1045	2.73 ± 0.008	10.41 ± 0.03
0.90 ± 0.04	47.5	745	2.39 ± 0.03	9.32 ± 0.10

Measurements

- Bunch length obtained from the bunch profile



Data analysis

- From: J. L. Laclare, CERN 87-03, p.264, CERN, Geneva, Switzerland (1987) we have

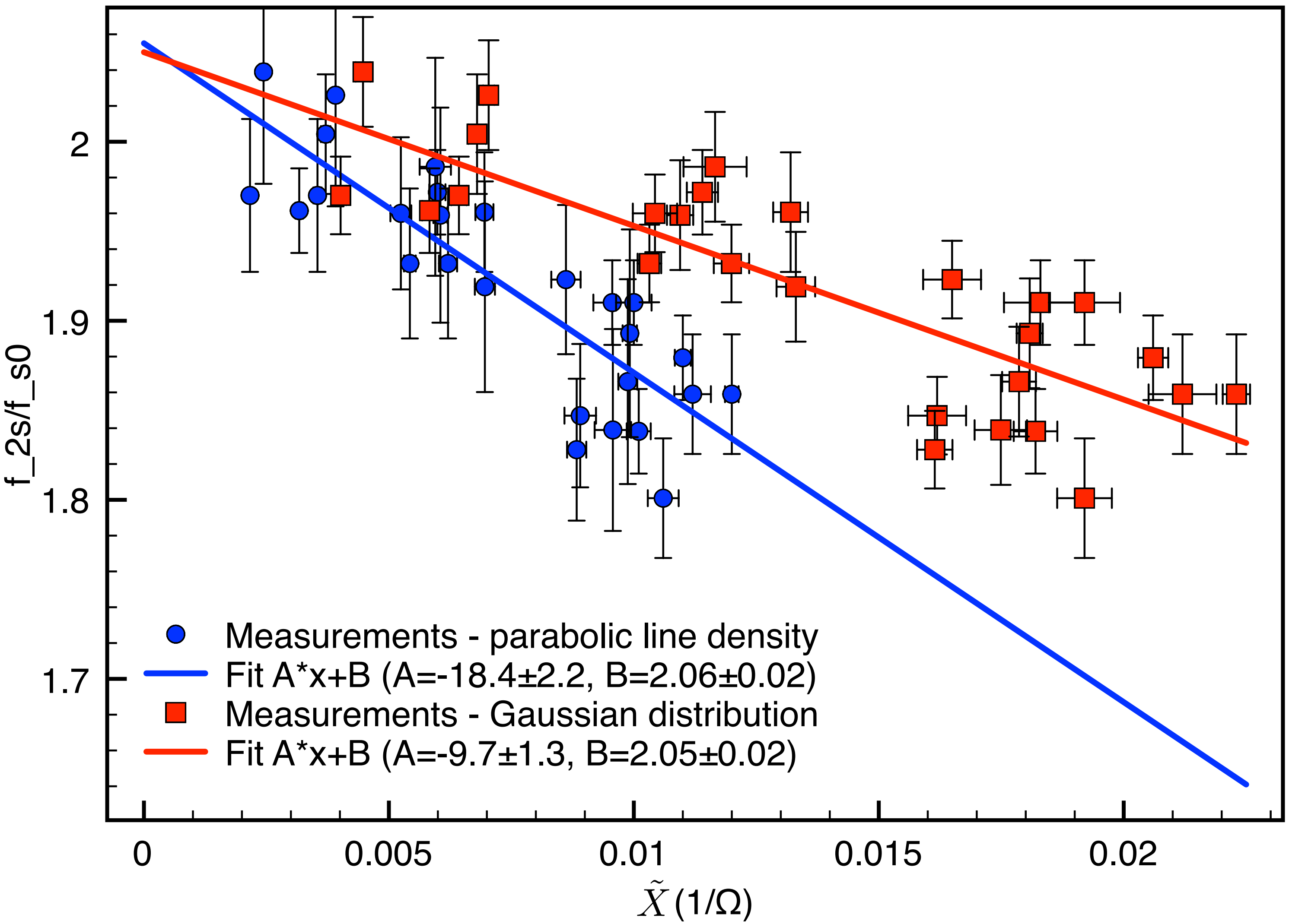
- Gaussian distribution:

$$\frac{f_{2s}}{f_{s0}} = 2 + \frac{eN_p}{\sqrt{2\pi}V_{RF}h\cos\phi_s\omega_0^2\sigma_G^3}\frac{Im[Z(p)]}{p} = 2 - \tilde{X}\frac{Im[Z(p)]}{p}$$

- Parabolic line density distribution

$$\frac{f_{2s}}{f_{s0}} = 2 + \frac{12eN_p}{V_{RF}h\cos\phi_s\omega_0^2\tau_b^3}\frac{Im[Z(p)]}{p} = 2 - \tilde{X}\frac{Im[Z(p)]}{p}$$

Data analysis



Data analysis

- About the factor of two: also Laclare found it ...

If we consider a parabolic line density bunch (26) interacting with a constant $I_m(Z_\parallel(p)/p)$, then, without any approximation, equation (56) can be reduced to

$$\ddot{\tau} + \omega_{s_0}^2 \tau = \frac{3 I \omega_{s_0}^2}{\pi^2 V_{RF} h \cos\varphi_s B^3} j Z_\parallel(p) \tau \quad . \tag{64}$$

In this particular case, the focusing force is purely linear. The corresponding incoherent frequency shift is given by

$$\Delta = \frac{\omega_s^2 - \omega_{s_0}^2}{\omega_{s_0}^2} = \frac{3 I}{\pi^2 V_{RF} h \cos\varphi_s B^3} j \frac{Z_\parallel(p)}{p} \tag{65}$$

which is about two times less than (62).

→ **Parabolic amplitude**

Data analysis

- About the factor of two: the difference is related to the method used to get the frequency shift.
- The starting equation is the same:

$$\ddot{\tau} + \omega_{s0}^2 \tau = \frac{e N_p \omega_{s0}^2}{2\pi V_{RF} h \cos\phi_s} \sum_{p=-\infty}^{\infty} Z(p\omega_0)\sigma_0(p\omega_0) e^{ip\omega_0 \tau}$$

- In case of parabolic line density distribution interacting with a pure inductive impedance, the summation can be expressed in a closed form and it gives directly a linear force

$$\sum_{p=-\infty}^{\infty} p\sigma_0(p\omega_0) e^{ip\omega_0\tau} = i\frac{3\pi\tau}{\omega_0^2(\tau_b/2)^3}$$

- In case of Gaussian distribution, the exponential term is expanded in series and only the linear term is taken into account

$$\ddot{\tau} + \omega_{s0}^2 \tau = \frac{e N_p \omega_{s0}^2}{2\pi V_{RF} h \cos\phi_s}$$

$$\sum_{p=-\infty}^{\infty} Z(p\omega_0)\sigma_0(p\omega_0) \left(1 + ip\omega_0\tau - \frac{(p\omega_0\tau)^2}{2} + \dots\right)$$

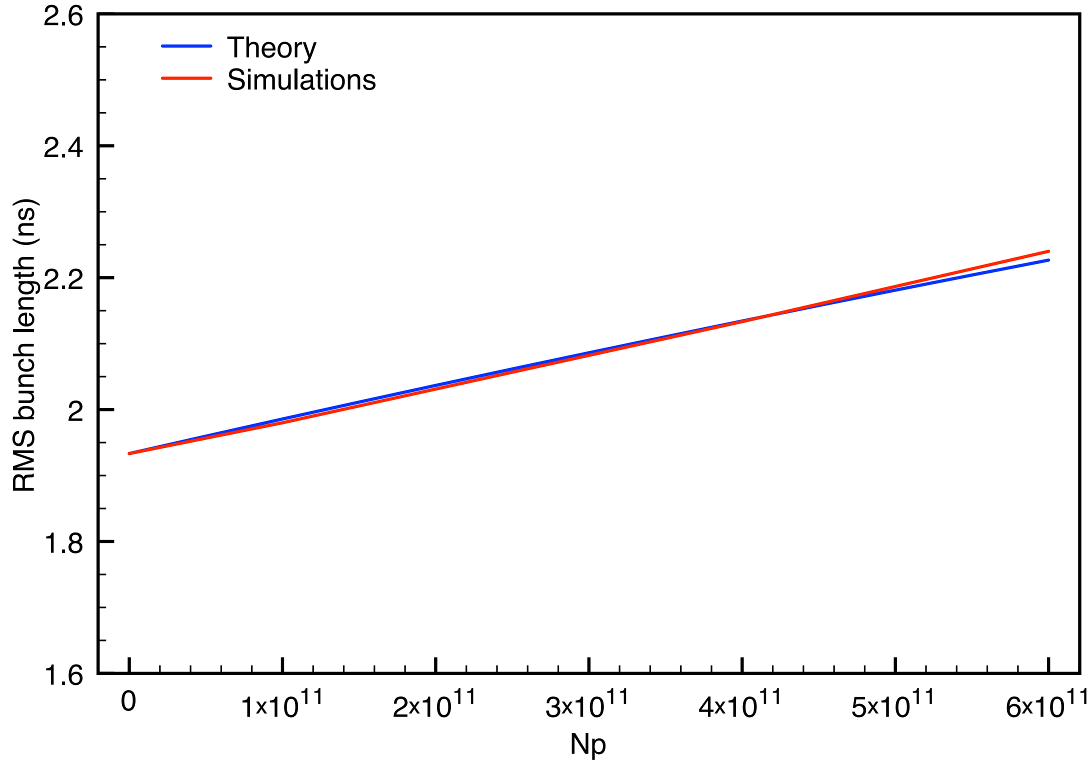
Comparisons with simulations

- Simulations can give an indication about the more suited method for determining the PS impedance.
- We used the tracking code initially developed to study the longitudinal beam dynamics in the electron storage ring DAΦNE at LNF-INFN and adapted to the beam parameters of the PS.
- As a check, we compared the bunch length vs intensity obtained with the theory and with simulations.

$$\left(\frac{\sigma_z}{\sigma_{z0}}\right)^3 - \left(\frac{\sigma_{z0}}{\sigma_z}\right) - \frac{3}{16}\frac{eN_pc^3}{\sigma_{z0}^3\omega_0^2 hV_{RF}}\frac{Z(p)}{p} = 0$$

Comparisons with simulations

- Bunch length as a function of intensity obtained with simulations and theory, by using Im[Z(p)]/p = 18.4 Ω and V_{RF} = 100 kV



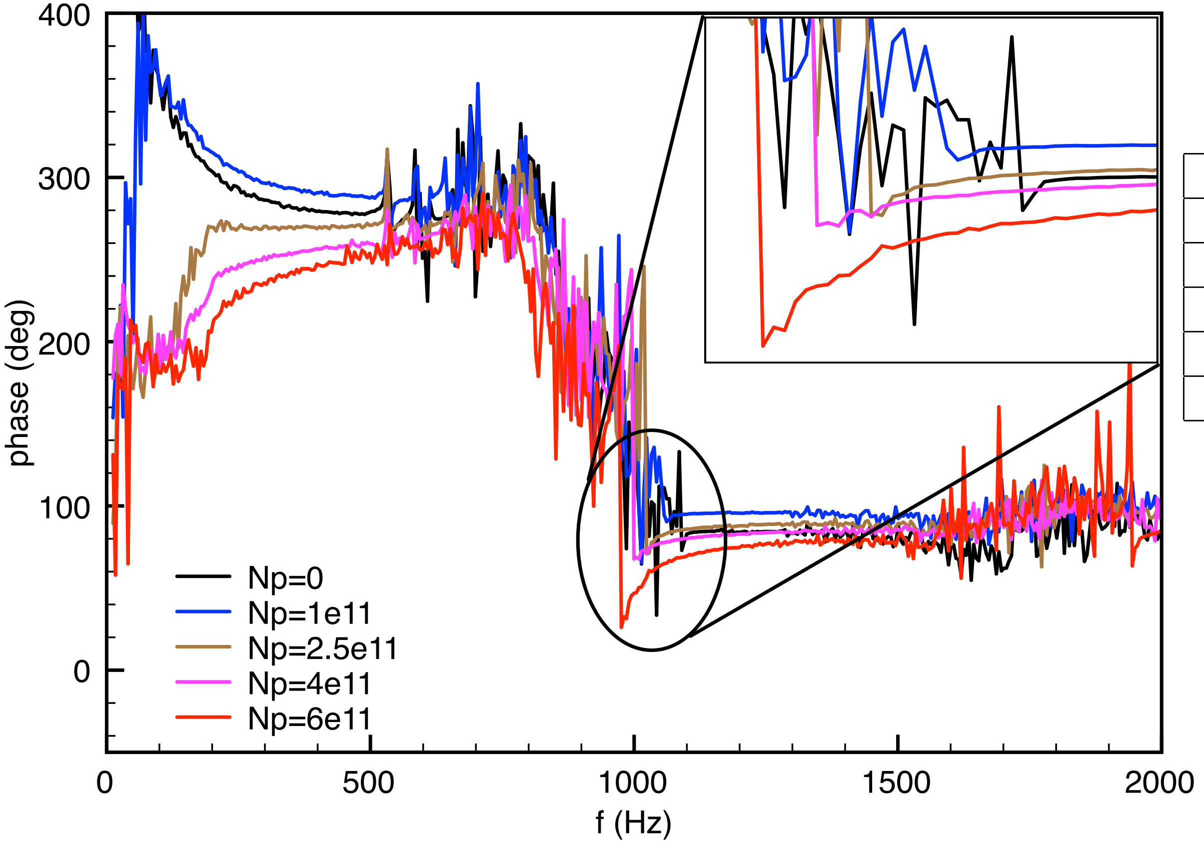
Comparisons with simulations

- We tracked the synchrotron oscillations of each macro-particle, and, by means of the FFT, obtained the corresponding frequency spectra.

- By including the collective effects due to the wake fields, an incoherent quadrupole frequency shift as a function of beam intensity, can be extracted.

- We used an impedance $Im[Z(p)]/p = 18.4\ \Omega$ and performed the same analysis we did for the measurements.

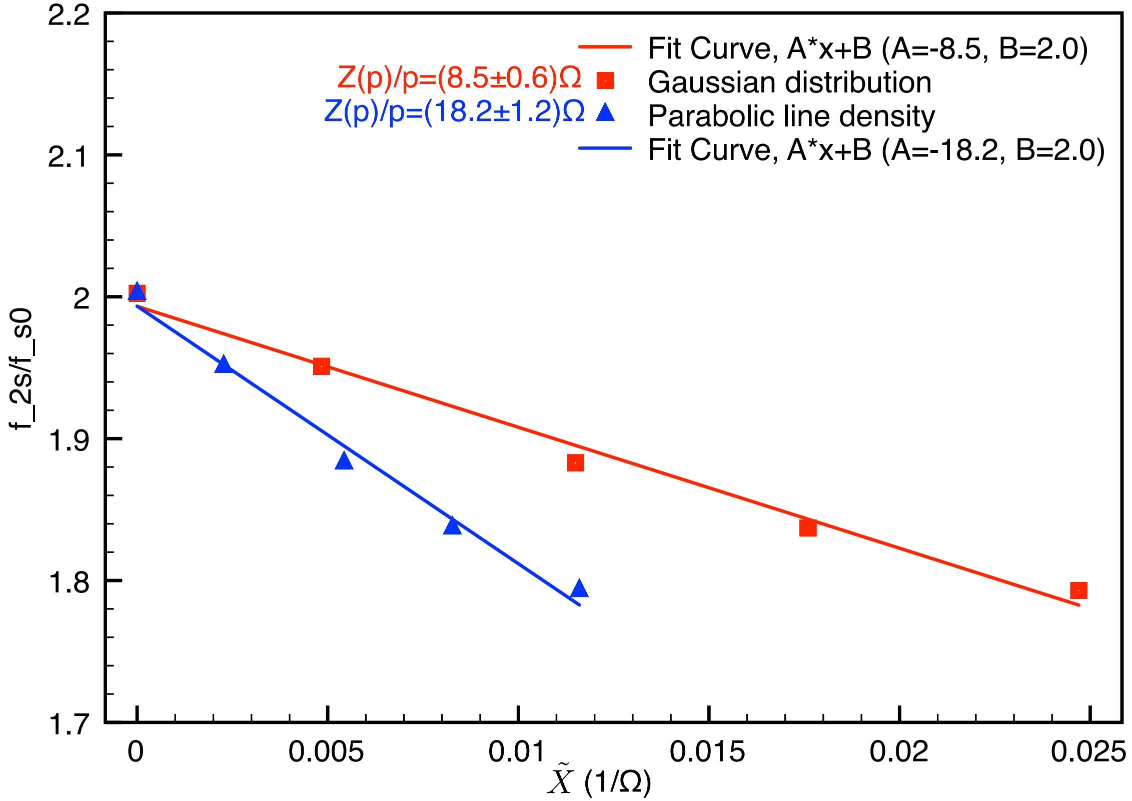
Comparisons with simulations



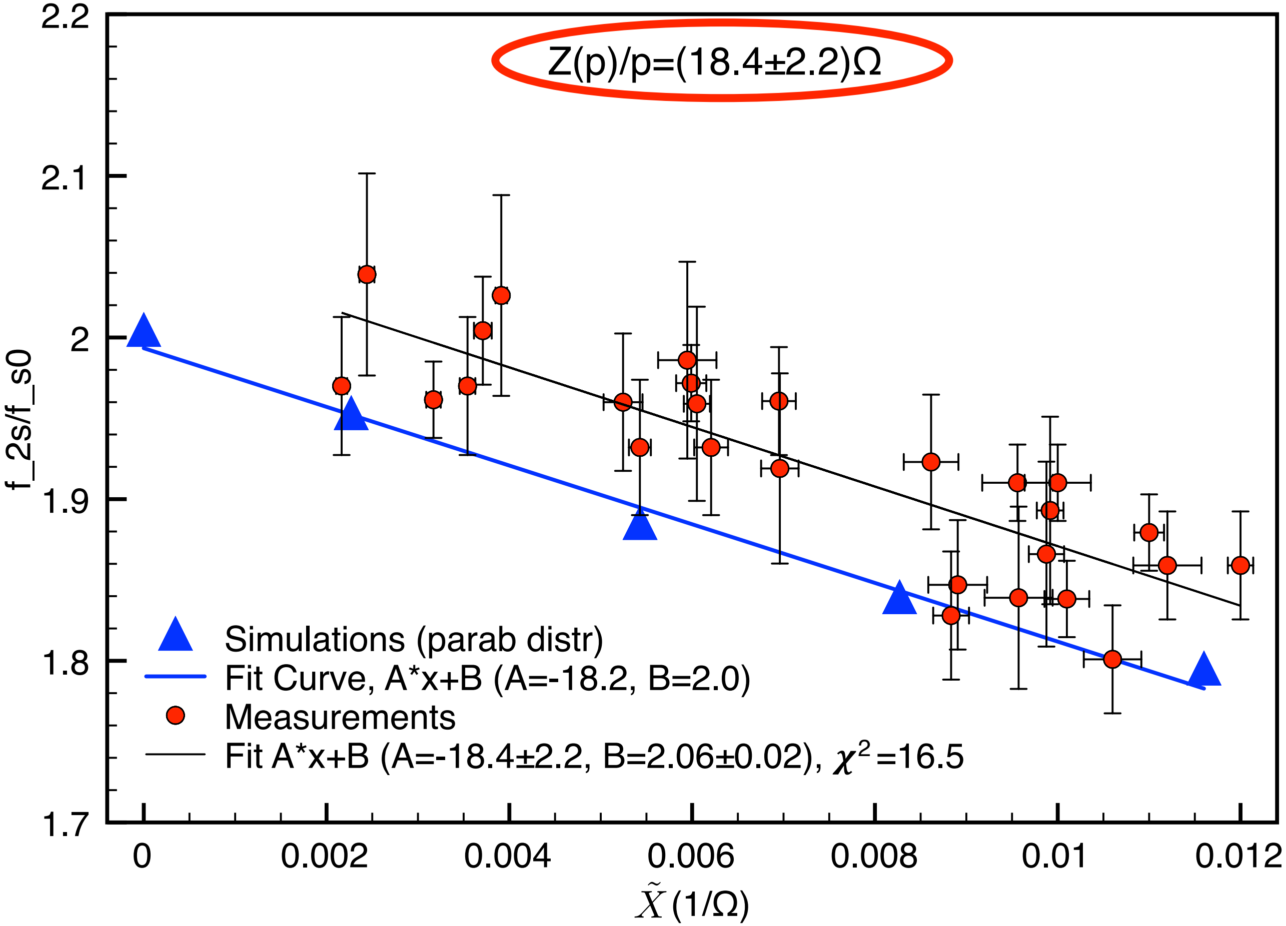
Np (10^{11})	f_{2s} (Hz)	σ_G (ns)	τ_b (ns)
0	1090	2.57	9.89
1	1062	2.60	10.01
2.5	1025	2.64	10.16
4	1000	2.68	10.32
6	976	2.74	10.55

Comparisons with simulations

Quadrupole frequency shift and linear fit with Gaussian and parabolic line density distributions by using the simulation results.



Comparisons with simulations



Considerations:

- **good quality of the beam, in particular of the longitudinal properties**
- **good diagnostics to control the longitudinal emittance**
- **reproducibility (monitor the BB impedance over the coming years)**

Comparisons with simulations

Im[Z(p)]/p = (18.4 ± 2.2) Ω

Broadband Longitudinal Impedance from Incoherent Quadrupole Frequency Measurements (2001)

J. Bento, R. Garoby, S. Hancock, J.-L. Vallet

|Z/n|≃ (21.7 ± 5.1) Ω

MEASUREMENTS OF THE PS LOW-FREQUENCY INDUCTIVE BROAD-BAND IMPEDANCE

R. Cappi, M. Giovannozzi, E&G. Metral, R. Steerenberg
J. Bento, R. Garoby, S. Hancock, J.L. Vallet

- **Measurements in 2000 ⇒ Good agreement between the 3 methods**

$$\mathrm{Im}\left[Z_l^{BB}(p)/p\right] \approx 20\ \Omega$$

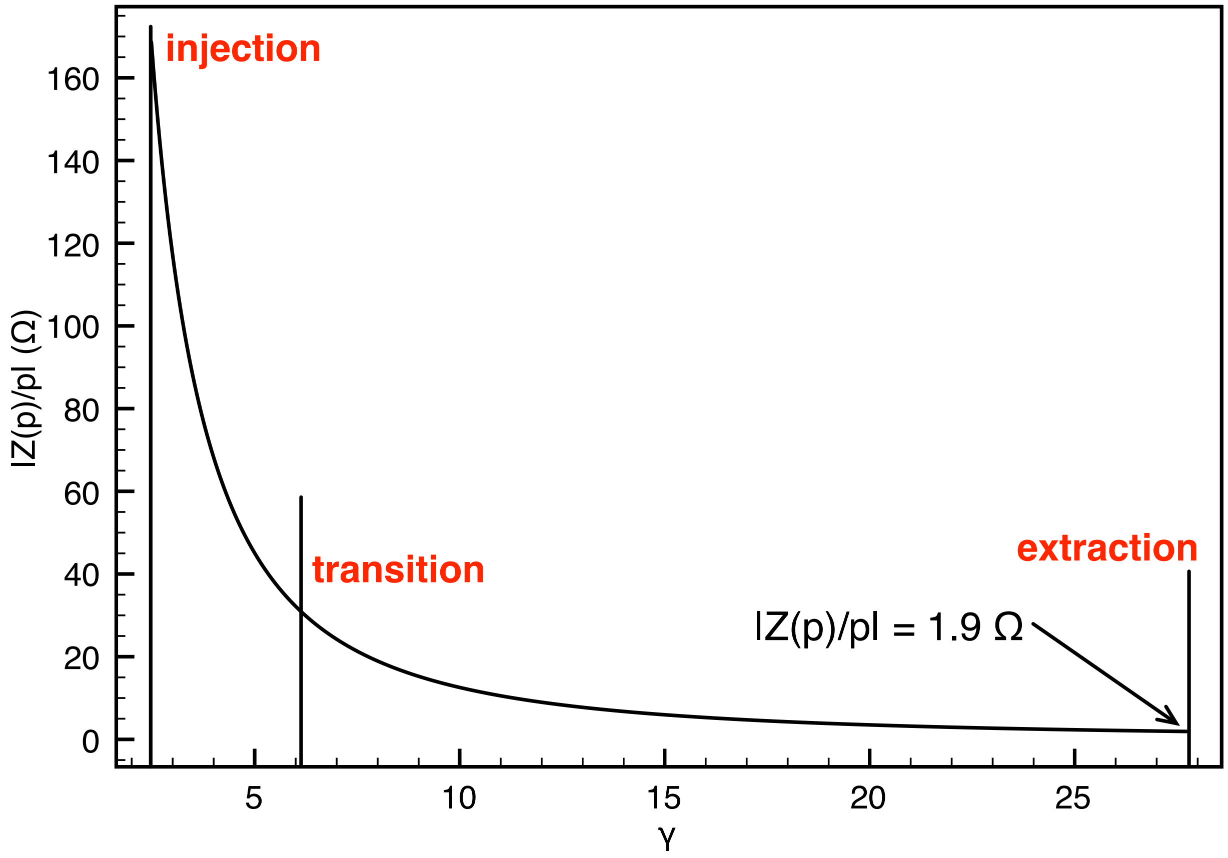
In agreement with the measurements done in the past

Outline

- Measurements the quadrupole incoherent synchrotron frequency shift vs single bunch intensity
- Results of data analysis and longitudinal broadband impedance value
- Comparisons with simulations
- Impedance budget
- Conclusions

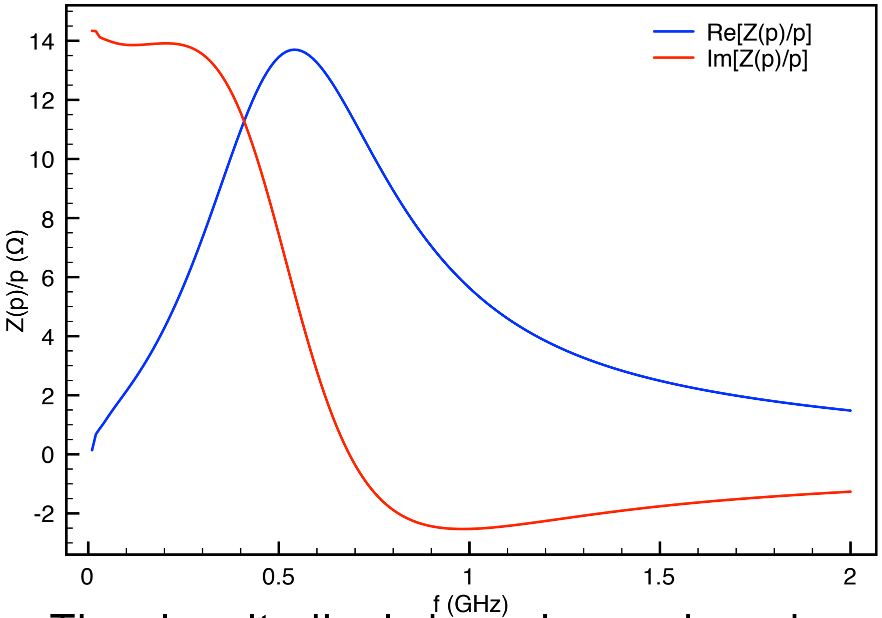
Impedance budget

- Space charge $$\frac{Z(p)}{p} = -i\frac{Z_0}{\beta\gamma^2}g_l \qquad g_l = \ln\frac{b}{a} + \frac{1}{2}$$



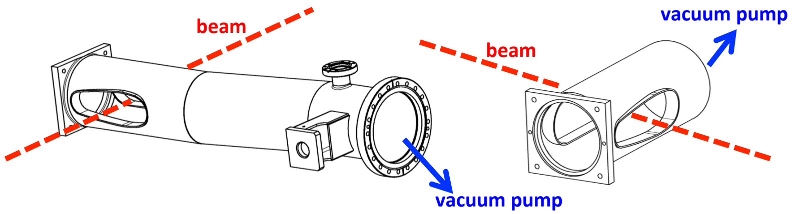
Impedance budget

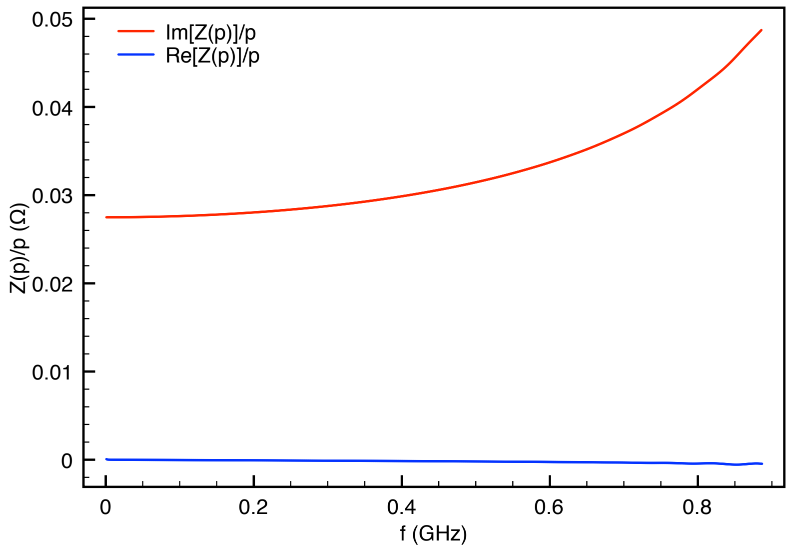
- Ferrite loaded kickers



The longitudinal impedance has been evaluated by using the field matching technique (Tsutsui), which was shown to be in good agreement with measurements and CST Microwave Studio simulations

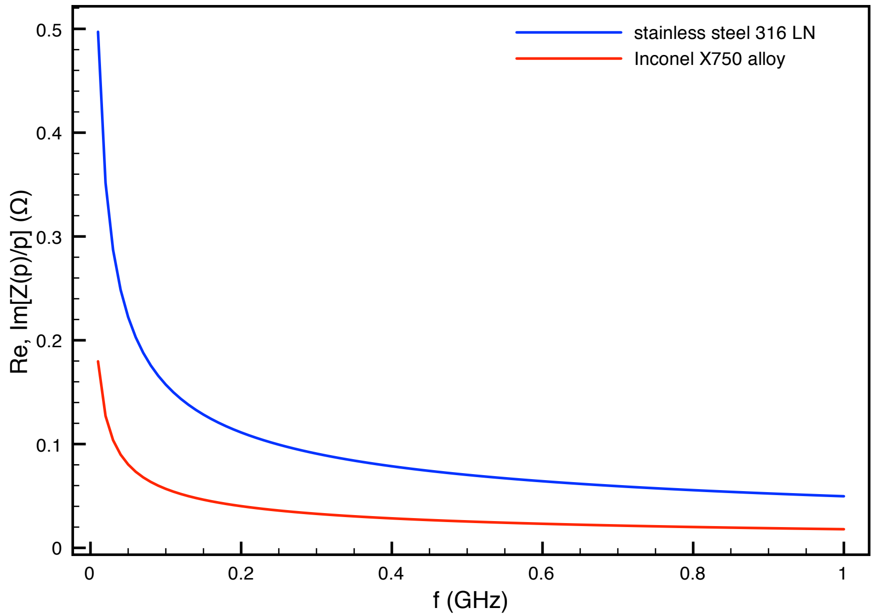
- Connections between beam pipe and vacuum pumps (CST simulations)





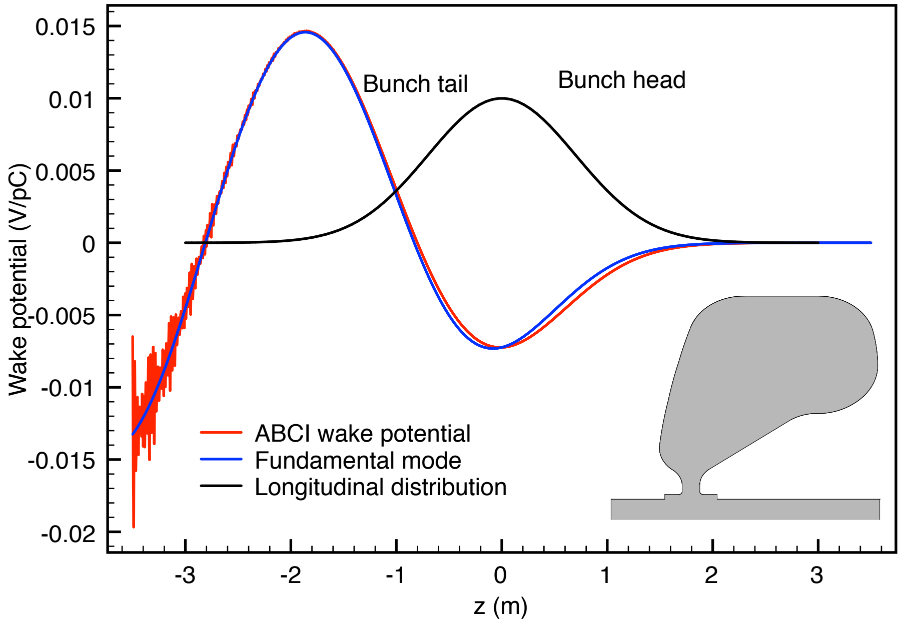
Impedance budget

- Resistive wall



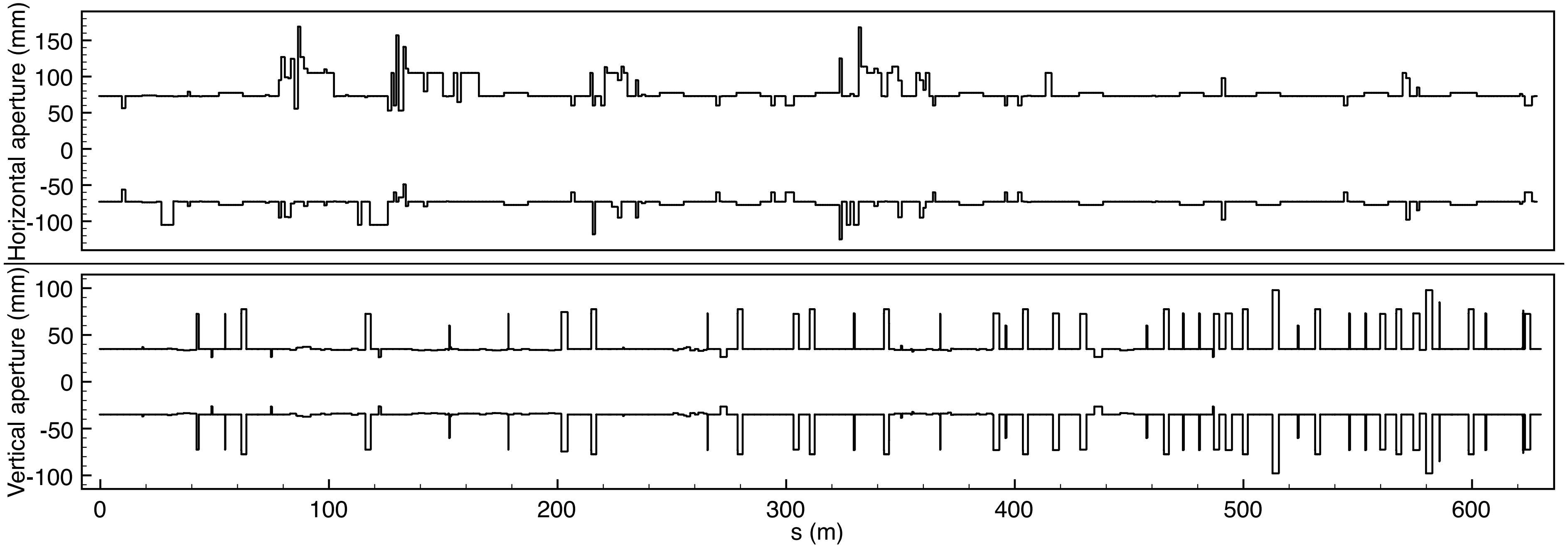
- 10, 40, 80 MHz cavities: resonant modes

e.g . 80 MHz cavity wake potential of a 2.3 ns Gaussian bunch



Impedance budget

- Step transition (average 35x73 mm ➔ 73x73 mm)

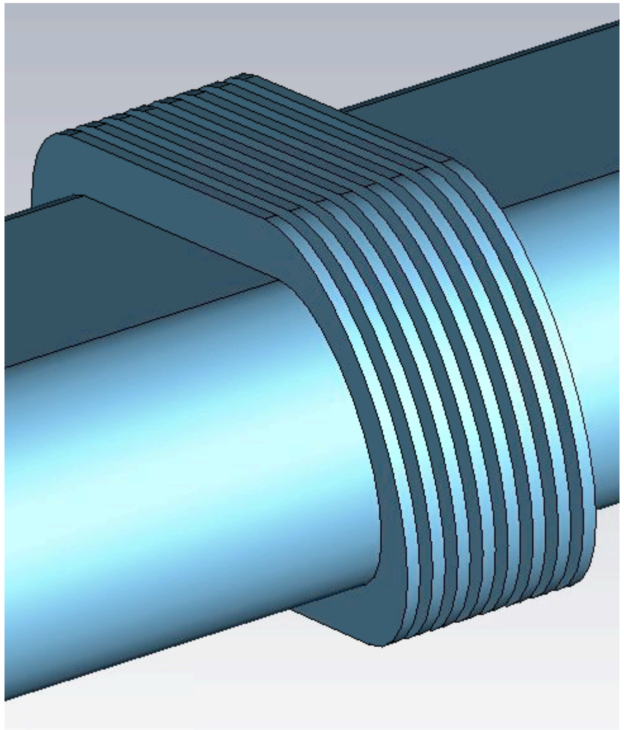


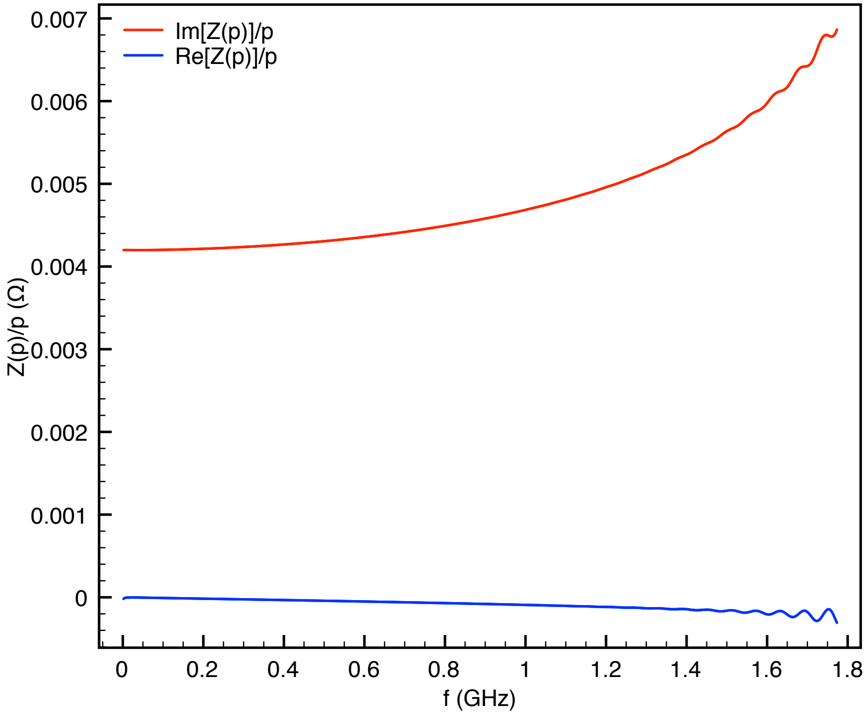
$$\frac{Z(p)}{p} = i\frac{\omega_0 Z_0 h^2}{4\pi^2 bc}\left(2\ln\frac{2\pi b}{h}+1\right)$$

$$Im[Z(p)]/p = 1.6\times10^{-2}\ \Omega$$

Impedance budget

- Bellows $$\frac{Z(p)}{p} = i\frac{n_c \omega_0 Z_0}{2\pi bc}\left(wh - \frac{w^2}{2\pi}\right)$$





Impedance budget

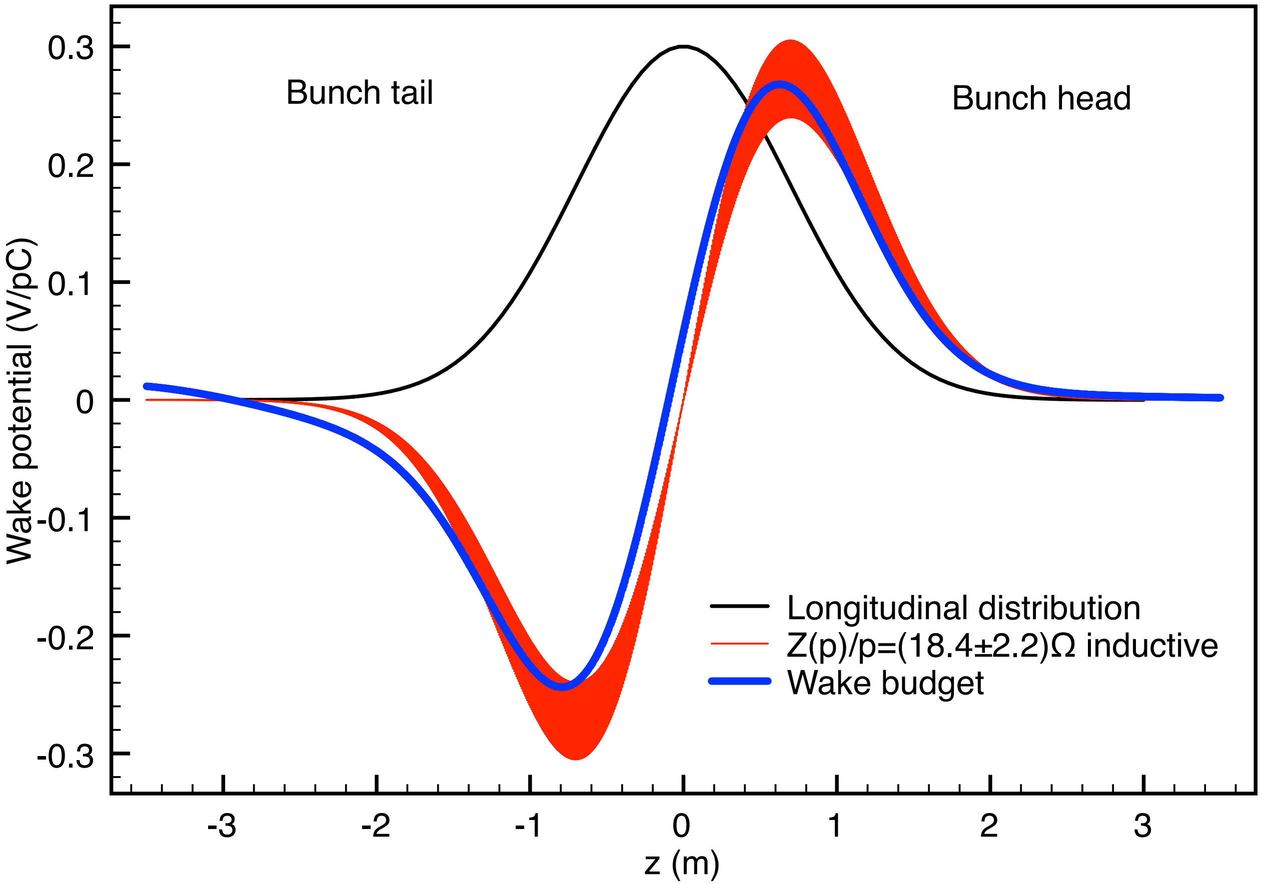
- Summary of impedance budget

Machine element	$Z(p)/p$ at $\omega = 1/\sigma_G$
Space charge	-1.9$i\Omega$
Magnetic kickers	(1.6+i·13.8)Ω
Pumping ports	2.8$i\Omega$
Resistive wall	$0.09(1+i)\Omega$
Steps	0.96$i\Omega$
Bellows	0.85$i\Omega$

f (MHz)	Q	R/Q (Ω)	Number of cavities	comment
7.6	5	30	10	
20	4.6	43.5	1	short-circuited
40	70	33	1	
80	100	56	2	

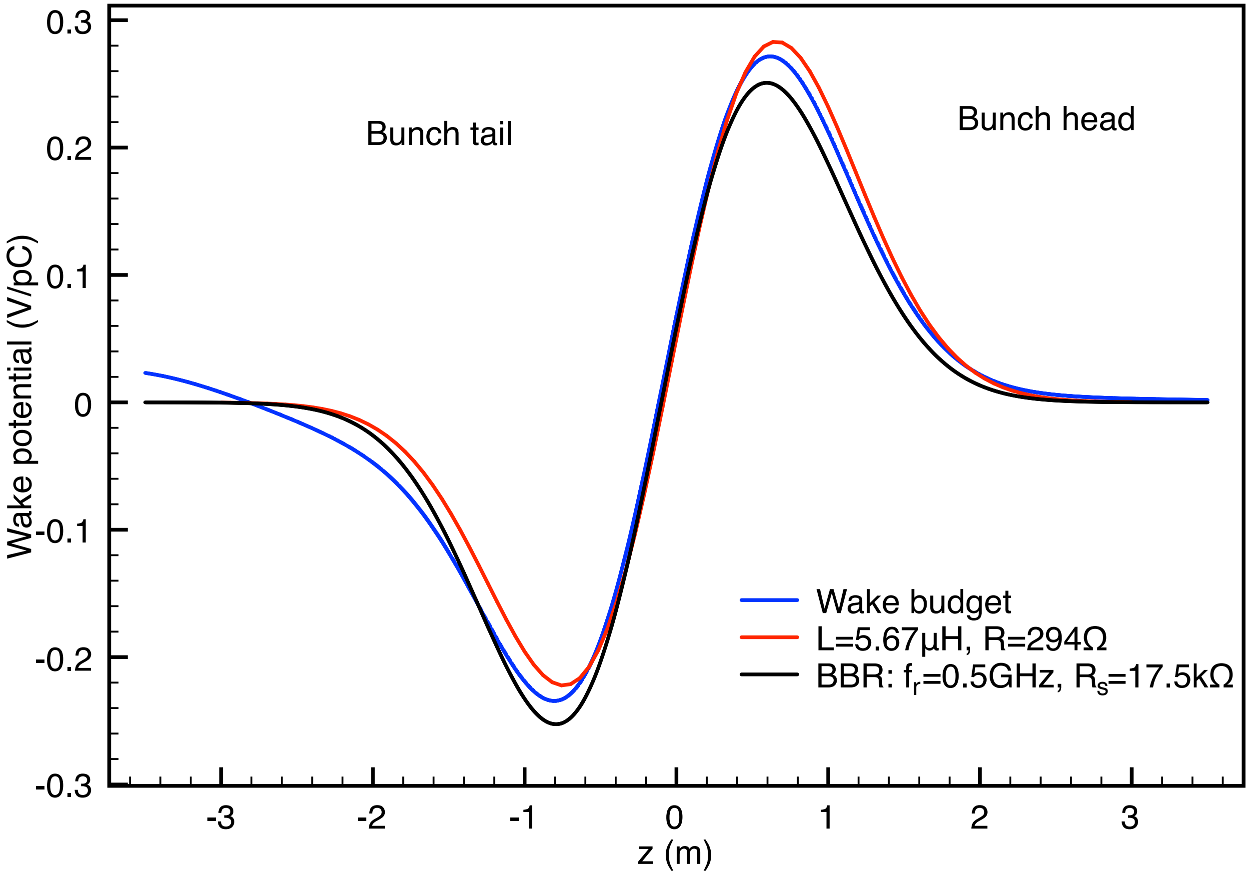
Impedance budget

- Total wake potentials of a 2.3 ns Gaussian bunch



Impedance budget

- Two improved models of the PS longitudinal broadband impedance



Conclusions

- Two MD sessions were dedicated to the measurements of the quadrupole incoherent synchrotron frequency shift.
- The obtained longitudinal broadband impedance $Im[Z(p)]/p = (18.4 \pm 2.2)\ \Omega$ is consistent with past measurements.
- We have good quality measurements in terms of beam characteristics, diagnostics to control the longitudinal emittance, and reproducibility.
- It is possible to monitor the PS broadband impedance over the coming years.
- The total longitudinal impedance budget obtained as a sum of different contributions (ferrite kickers, pumps connections, RF cavities, ...) is in a very good agreement with the measured impedance.
- The obtained broadband impedance model can be used in a simulation code to study the longitudinal beam dynamics under the effects of wakefields.

Conclusions

- Thanks to the PS operations team for the help in setting-up the beams and to ... many people for useful discussions and suggestions!
- Thanks to BE/ABP group for the help and the warm hospitality during my stay at CERN: it has been an exciting and positive experience!

THANK YOU!

... and ... to next year!

COULD IT BE A THREAT?